Manufacture of Alloy Steel Tube by High Frequency Electric Resistance Welding*

By Hirohisa ICHIHARA,** Daigo SUMIMOTO,** Tsurugi KIMURA,** Yasuo KIMIYA*** and Mitsuo YOSHIZAWA***

Synopsis

The quality of chromium, chromium-molybdenum and austenitic stainless steel tubes manufactured by an electric resistance welding (ERW) is highly dependent on the sophisticated technologies of non-oxidizing welding, precise control of welding energy and smooth cutting of inside flush. In this report a newly developed manufacturing technology for ERW alloy steel tubes is described on the following items; oxygen content in the welding atmosphere for a non-oxidizing welding and its control equipment, appropriate welding energy and its control system and a high performance impeder.

Furthermore, the quality of the mass-produced ERW alloy steel tubes by the new technology is investigated focusing on their corrosion resistance, high temperature creep rupture strength and fatigue strength.

I. Preface

It is mainly ascribed to the recent development of high frequency electric resistance welding (HF-ERW) technology that ERW tubular products have been widely accepted in the market. However the application of high-frequency ERW has been limited to low-carbon steel tubes, because of the inability to ensure the stability of product quality with high-carbon (carbon content: 0.4 to 0.6 %), low-alloy and stainless steels.

Mass production of ERW alloy steel tube at Nippon Steel Corporation (NSC) began in the 1970's with boiler superheater tube for large power plants (ASTM A213 T12 Equivalent/JIS G3462 STBA22). This was made possible by advances mainly in high-purity steel making, high frequency electric-resistance welding, and nondestructive testing that were achieved about that time. Today chromium, chromium–molybdenum and austenitic stainless steel tubes are made by HF-ERW.

Today’s major applications of alloy steel tube can be broadly classified into two groups: The first group comprises tubes for piping and heat exchanging. They require adequate corrosion resistance and strength at elevated temperature. Low-carbon chromium–molybdenum and nickel–chromium (austenitic stainless) steels are the main materials used. The second group consists of mechanical tubes of high-carbon chromium and chromium–molybdenum steels that are required to possess high strength, abrasion resistance and hardenability. The tube wall thickness varies extensively from light to extra-heavy.

This paper introduces the technologies developed to enhance and stabilize the quality of the weld of ERW alloy steel tubes and the properties of the tubes mass-produced by employing such technologies.

II. New Welding Technologies for ERW Alloy Steel Tube

Main problems with the weld of ERW alloy steel tube are that
1) chromium oxides are apt to remain in the weld and impair quality, and
2) a drop in welding speed with small-diameter heavy-wall tubes entails greater difficulty in removing cooled inside flush.

The solution for each problem is as follows:

Problem (1): Prevent the formation of oxides during welding the edges of formed skelp and facilitate the squeezing out of formed oxides during welding.

Problem (2): Increase the welding speed by enhancing welding heat efficiency in order to cut inside flush at higher temperature.

1. Inert-gas Shielded Welding

Photograph 1 is a micrograph of the cross section of an ERW stainless steel tube (ASTM A312 TP304/ JIS G3459 SUS 304 TP) showing the influence of the inert-gas shielding on the quality of the weld. Photograph 2 shows the fractured surface of the weld observed under a scanning electron microscope (SEM),

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** Kimitsu R & D Laboratory, Nippon Steel Corporation, Kimitsu, Kimitsu 299-11.
*** Kimitsu Works, Nippon Steel Corporation, Kimitsu, Kimitsu 299-11.
with the arrow indicating a typical weld defect. Analysis by electron probe microanalyzer (EPMA) revealed that the defect consisted of a composite oxide made up mainly of chromium, manganese, silicon and iron as shown in Table 1.

The oxide has such a high melting point that it is difficult to melt and, therefore, to squeeze out from the weld together with the molten metal during welding.

Figure 1 shows the relationship between the chromium content in alloy steel and the appropriate range of welding energy (in which no weld defect occurs). The higher the chromium content, the narrower the appropriate range of welding energy. This tendency is particularly pronounced when welding is performed in the atmosphere.

The quantity of chromium oxide produced increases with an increase in the chromium content of steel and the oxygen concentration in the atmosphere during welding. As the quantity of chromium oxide increases, larger welding energy is required to permit its discharge by electromagnetic forces. At the same time, an increase in the quantity of alloying element (i.e., chromium) lowers spattering temperature due to the decrease of melting point and, as a consequence, narrows the appropriate range of welding energy. When welding is performed in an inert-gas atmosphere, the quantity of chromium oxide produced is so small that the range of appropriate welding energy is not narrowed significantly. On the other hand, industrial control limit of welding energy in HF-ERW is about 5 %. Accordingly, as may be derived from Fig. 1, defect-free welding in the atmosphere is possible in the case of the chromium content in the steel below 1.0 %.

Figure 2 shows the relationship between the oxygen concentration in the welding atmosphere and the range of welding energy applicable to the inert-gas shielded welding of stainless steel (ASTM A312 TP-304). As may be seen, the oxygen concentration should be kept below 0.1 % for defect-free welding.

Figure 3 shows an inert-gas shielded welding apparatus. This apparatus is capable of controlling the oxygen content in the welding atmosphere below approximately 20 ppm, resulting in non-oxidizing welding.

Table 1. Chemical composition of weld defect. (%)

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>Mn</th>
<th>Ni</th>
<th>Cr</th>
<th>Fe</th>
<th>O</th>
<th>Al</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Example 1</td>
<td>13.5</td>
<td>21.4</td>
<td>1.4</td>
<td>27.9</td>
<td>16.9</td>
<td>18.4</td>
<td>0.1</td>
<td>0.02</td>
</tr>
<tr>
<td>Example 2</td>
<td>16.3</td>
<td>24.0</td>
<td>2.2</td>
<td>23.7</td>
<td>22.7</td>
<td>11.4</td>
<td>0.3</td>
<td>—</td>
</tr>
</tbody>
</table>

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P_e = \frac{P_t - P_{ef}}{P_t} \times 100
\]

- \( P_e \): Appropriate range of welding energy
- \( P_t \): Welding energy just below spattering
- \( P_{ef} \): Welding energy just above incomplete fusion

\( v = 40 \text{ m/min} \)

Fig. 1. Effect of chromium content on appropriate range of welding energy.

\( v = 40 \text{ m/min} \)

Fig. 2. Effect of oxygen concentration in atmosphere on appropriate range of welding energy.

2. Automatic Welding Energy Control System

As mentioned previously, precise welding energy control expands the applicability of ERW in the atmosphere to alloy steels. It is also indispensable for the prevention of the occurrence of penetrator. Research conducted by Haga et al., has thrown light on the mechanism by which penetrator occurs. From his conclusions and mill operation experiments, it is indicated that the occurrence of penetrator is closely related to the spattering.

Figure 4 shows the range of welding energy in which no penetrator will occur. The range is extremely narrow when the welding speed is low and expands as the welding speed increases. However, the skill of operators has its limit in steadily controlling the welding energy within such a range. The weld quality will not be stable unless the control system is capable of maintaining the optimum welding condi-
tion by continuously controlling welding energy according to changes in various parameters, especially skelp thickness, during welding.

Figure 5 shows an automatic welding control apparatus. This apparatus has a function to continuously feed forward the variation of skelp thickness and welding speed, a function to continuously feed back welding temperature, and a function to control welding current (anodic secondary voltage) so that the optimum welding temperature is maintained on the basis of the feed-forward and feed-back information processed by computer.

Figure 6 shows that this system can keep the welding temperature constant even if skelp thickness varies (for example, at a weld joint of two skelps). This in turn permits attaining stable weld quality and minimizing the tube loss that might occur in the vicinity of skelp weld-joint.

3. High-performance Impeder

Mechanical tubes of high-carbon and alloy steels are often of small diameter and heavy wall thickness. It is not uncommon that the ratio of wall thickness to outside diameter \((t/d)\) exceeds 20% and the inside diameter is smaller than 1 inch. An impeder to be inserted in such tubes must be small. This results in a drop in welding heat efficiency, that is, welding speed and an increased difficulty in removing the inside flush.

It is known that the drop in the welding speed of small-diameter heavy-wall tubes is due to a decrease in the cross-sectional area of an impeder (magnetic material). Therefore, research was conducted to make up for the reduction in the cross-sectional area of the impeder by increasing its saturation flux density. It is found that silicon steel having a high saturation flux density \((B_s=20\,000\,\text{gauss})\) can be used for the purpose. Despite the much higher saturation flux density than that of ferrite \((B_s=5\,000\,\text{gauss})\), silicon steel used to be regarded as unsuitable for an impeder because its specific electric resistance is as low as 45 \(\mu\Omega\cdot\text{cm}\). The eddy current generates great heat in a high-frequency magnetic field and makes it impossible to keep the impeder at a temperature below the Curie point. Silicon steel foils of small cross-sectional area arranged in insulated layers are now put to practical use as they do not generate much heat and improve cooling efficiency.
Figure 7 shows a cross-sectional view of an impeder assembly of silicon steel. Figure 8 shows an increase in welding speed and a decrease in power consumption achieved by the impeder, compared with those of conventional ferrite impeders. The welding speed with the new impeder is 50%, maximum, higher than that of the conventional ferrite impeder.

III. Weld Quality of ERW Alloy Steel Tubes

We have been engaged in the production of ERW alloy steel tubes for a period of over 10 years. ERW alloy steel tubes have found use in many applications as plant tubing, heat exchanger and important parts of automobiles and other machinery, both at home and abroad. The properties of the ERW alloy steel tubes massproduced for such applications are described in the following.

The quality of the weld of ERW tube should be evaluated in comparison with that of the base metal. The comparison was made from many aspects using such simple tests as flattening and flaring tests, tensile and impact tests at elevated and low temperatures, corrosion, high-temperature creep and fatigue tests.

Table 2 lists the specification, size, chemical composition and tensile properties of the products to be discussed.

Fig. 7. Structure of silicon steel impeder (cross section).

Fig. 8. Effect of impeder materials.
1. Stainless Steel Tubes for Piping (ASTM A312 TP304, TP316L, JIS G 3459 SUS304 TP, SUS316L TP)

Stainless steel tubes for plant piping are required to have high tensile strength, ductility, toughness and corrosion resistance over a wide range of temperatures. Additional requirements particularly for ERW tubes are to ensure that homogeneous microstructure and chemical composition are attained in their weld and base metal.

1. Microstructure

Photograph 3 shows photomicrographs of the cross sections of tubes as-welded and solution-treated. The specimens have been electrolytically etched in a 10% solution of oxalic acid. The as-welded tube in Photo. 3(1) exhibits a white resolidified layer along the weld line, with obvious upright metal flow on both sides. Solution treatment, as shown in Photo. 3(2), extinguishes the resolidified layer and the same austenitic structure in the weld as in the base metal is obtained.

2. Chemical Composition at The Welded Portion

Figure 9 shows the concentration distribution, determined by EPMA, of nickel, chromium and carbon, which are the principal elements, in and around the resolidified layer of molten metal in the specimen shown at (1) of Photo. 3. As is obvious, the investigated region proved to be homogeneous in terms of chemical composition, exhibiting no concentration nor dilution of the elements.

3. Flattening and Flaring Tests

Photograph 4 shows a flattened tube sample. The specimen was fully flattened until opposite walls met. Even then, no crack occurred in the weld, as indicated by an arrow, where maximum tensile stress was applied. Photograph 5 shows a flared tube sample. No crack occurred in the edge of the tube that was conically expanded.

4. Tensile Strength

For the evaluation of the strength of weld a direct comparison of tensile strength between the weld and base metal is carried out (see Fig. 10). The test results at temperatures between −196 °C and 850 °C are shown in Fig. 11. As may be seen, the specimens with and without the weld exhibited the same fracture.
characteristics.

5. Corrosion Resistance

(1) 65 % Nitric Acid Test (Immersed 5 times, 48 hr each, in a boiled 65 % solution of nitric acid)

The specimens tested exhibited no intergranular corrosion, with only very little corrosion-induced weight loss, as shown in Photo. 6.

(2) 5 % Sulfuric Acid Test (Immersed in a boiled 5 % solution of sulfuric acid for 48 hr)

The test result exhibited no selective corrosion in any particular localities. The corrosion observed was uniform and slight (see Photo. 7).

(3) Ferric Chloride Test (Immersed in a solution containing N/20 hydrochloric acid and 50 g/l FeCl₃ at 40 °C for 48 hr)

Photograph 8 and Fig. 12 show the depth and density of pitting on the specimens immersed in a solution of hydrochloric acid containing ferric chloride. No specific point or area is proved to be particularly susceptible to pitting corrosion.

2. Chromium–Molybdenum Steel Tubes for Boilers (ASTM A213 T22 Equivalent/JIS G3462 STBA24 Equivalent)

Creep-rupture strength at elevated temperatures is extremely important with this type of tubes which are

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Photo. 4. Flattening test (TP304).

Photo. 5. Flaring test (TP304) 1.5D.

Photo. 6. 65 % nitric acid test (TP316L).

Photo. 7. 5 % sulfuric acid test (TP316L).

Weight loss: 0.34 g/m²-h

Weight loss: 0.011 g/m²-h
used as the super-heater tubes of large power plants. The creep-rupture test was conducted using specimens of circular cross section worked parallel and perpendicular to the ERW weld line and specimens for an internal pressure creep rupture test shown in Fig. 13.

Figure 14 shows the relation between applied stress and time to rupture. The same curves were obtained irrespective of the shape of specimens, presence of the weld and the direction of the weld line. Figure 15 shows the same test results rearranged by use of the Larson–Miller parameter. As will be seen, the 100 000-hr rupture strength derived from the allowable stress specified by ASTM Specification Section 1 is fully satisfied.

Photograph 9 shows the appearance of ruptured specimens subjected to an internal pressure creep rupture test, which demonstrate the soundness of the weld.

3. Chromium Steel Tubes for Mechanical Structure (ASTM A519 Gr5140 Equivalent)

Chromium steel tubes of heavy wall thickness are often used to make parts of rotating members carrying heavy loads. For these parts, a preliminary compression fatigue test is often made to evaluate their quality.
The results of a compression fatigue test shown in Fig. 16 indicate that the ERW weld has no influence on where crack initiates. The tested tubes exhibited uniform fatigue strength throughout their cross section.

IV. Summary

The newly developed welding technologies for alloy steel tube consist of inert-gas shielded welding, automatic welding energy control system and a high performance impeder. The investigation on quality of ERW alloy steel tube introduced here shows that the properties of the weld are in all respects homogeneous and equal to those of the base metal.

REFERENCE